IN THE UNITED STATES PATENT & TRADEMARK OFFICE

International Patent Application No.: PCT/DE2003/004129
International Filing Date: 11 December 2003
Paris Convention Priority Date: 13 December 2002
Inventors: Ter-Avetisyan et al.
For: Apparatus and Method of Making a Droplet Target

Translator's Certificate of Accuracy

I, Karl Hormann, being fluent in the English and German languages, hereby certify that the appended document is a correct and accurate English translation of the specification, claims and abstract of Applicants' International Application originally filed in the German language.

Karl Hormann

Given at Cambridge, Massachusetts,
this 13th day of June 2005

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English Translation of Applicants' Original German Specification

5   Apparatus and Method of Making a Droplet Target

The invention relates to an apparatus for making a droplet target
provided with at least one receptacle for receiving the target liquid in which a
high pressure is realized by means of gaseous nitrogen, a magnetic valve

10   connected to the receptacle and switchable in the ms range, and a nozzle, as
well as to a method.

Hereafter, devices known in the prior art will be described by which
liquid droplets are being generated wherein the interaction of laser beams

15   aimed at these droplets generates X-rays or extreme ultra-violet light. Such
rays are used, for instance, in microscopy and lithography.

U.S. patent No. 6,324,256 describing an arrangement of a laser
plasma source for generating EUV light, also refers to a device for making

20   droplet targets. The droplets made are of a diameter larger than the diameter
of droplets generated by a gas fed through a nozzle where it condenses to
form a cloud of clusters of extremely small particles. As described, a liquid is
formed from the gas by means of a heat exchanger which reduced the
temperature of the gas . The liquid is fed to a nozzle the opening of which

25   increases in the direction of the exit opening. The droplets are formed in this
section and then exit from the exit opening of the nozzle to interact with a
laser beam for generating EUV light. However, it is not possible in this
arrangement in a defined manner to set the size of the droplets. In this
arrangement the gaseous initial material is converted to a liquid one.

30   Moreover, the droplets interact with the laser very close to the nozzle which in
consequence of the heat and erosion is destroyed.

In Opt. Common. 103, 105 (1993), L. Ramble and H. M. Hertz report on an X-ray source in which droplets of ethanol are used as the target. To generate these droplets, ethanol was pressed at 30 to 50 at into a vacuum chamber through a capillary of about 10 µm diameter tapering in the direction of the nozzle. In order to generate a liquid volume - in this case of a diameter of 15 µm - pressure surges were piezo-electrically produced at a frequency of about 1 MHz. The relatively large droplets were used for examining the interaction with laser radiation in an intensity range of 10^{12} to 10^{14} W/cm^2 as described by O. Hemberg, B. A. M. Henson, M. Berlund and H. M. Hertz in J. Appl. Phys. 88, 5421 (2000). Since in this case each individual droplet is interacting and the laser focus is but slightly larger than the diameter of the droplets of ethanol, the drift problem of the droplet source is of major importance, the project is especially directed to solving an exact droplet-laser synchronization.

Super dense droplet spray of a density of up to 10^{19} atoms/cm^3 and a droplet diameter of about 1 µm was produced by a droplet source described by L. C. Mountford, R. A. Smith and M. R. H. R. Hutchinson in Rev. Sci. Instrum. 69, 3780 (1998) and is the basis of the instant invention. The basis of this droplet source is a magnetic valve which forms the pulse of liquid and, therefore, the volume of the liquid. A receptacle was filled with a liquid and kept under high pressure by means of methanol. The valve is opened in synchronism with the laser pulse and for 2,500 µs to allow droplets to emerge from the nozzle. It was possible to produce droplets of lesser diameter of about .6 µm by subsequent electrostatic cleaving of the droplets. This, however, requires a technically complex arrangement. However, the jog consisting of such droplets is of lower density, *viz.* about 10^{16} atoms/cm^3.

For effectively generating X-rays or EUV light it is necessary, however, to make available droplet targets of dimensions of the size of possible laser wavelengths (T. D. Donelly, M. Rust, I. Weiner, M. Allen, R. A. Smith, C. A. Steinke, S. Wilks, J. Zweiback, T. E. Cowan, and T. Ditmire, J. Phys. B: At.

Mol. Opt. Phys. 34, L313 (2001)) and, therefore, of a smaller diameter compared to the prior art, and which form a spray of an atomic density of > 10^{18} atoms/cm3.

5   It is thus an object of the invention to provide a way by which such droplet targets can be produced. The high density is also to be realized at a greater distance from the nozzle, i.e., the droplet target, compared to the prior art, is of a superior collimation in order to extend the useful life of the nozzle.

10   The object is accomplished with an apparatus of the type referred to *supra* in which the nozzle, in accordance with the invention, is constituted by an supersonic nozzle, the vale is connected to the supersonic nozzle by an expansion channel, heating means are formed around the expansion channel such that the temperature may be set at a level at which a super saturated

15   vapor is generated in the expansion channel, and an insulation is provided between the electromagnetic valve and the heating means.

The invention makes possible the generation of super dense sub-μ liquid targets required for examining the interaction between laser radiation

20   and plasmas. In contrast to the mentioned prior art generating droplets in the saturated gas phase, the droplets in accordance with the invention are generated from super saturated vapor which condenses into a cloud of spray. The target generated by the apparatus of the invention consists of droplets of an mean diameter of about 150 nm and is of an mean atomic density of >

25   10^{18} atoms/cm^3. Such a target makes it possible the examination of conditions hitherto not researched which exist between clusters (from several atoms to 10^{16} atoms/cluster of a local density approximating that of a solid) and solids. Moreover, relative to the advantages of a cluster target, the spatial extent of the droplets influences an increased volume charge limitation

30   of hot electrons which, in turn, results in an improved coupling of the laser energy with the ions of the droplets. Thus, a much hotter plasma can be generated and the effect in the X-ray conversion can be improved. The

droplet target produced withe the device of the invention can be generated continuously and is of chronologically unlimited operation.

Embodiments of the apparatus in accordance with the invention relate
5 to the structure of their individual components. The pulsed electromagnetic valve operates at a pulse length of 2 ms; the length of the expansion channel is from several mm to several cm and its diameter is from several 100 µm into the mm range; the supersonic nozzle has a conical opening angle 2Θ from several degrees to several 10°, an input opening of several 100 nm diameter
10 and a conical section of a length of several mm. After pressing the target liquid upon opening of the valve into the expansion channel where as a result of the heating a supersaturated water vapor is present, it will expand during passage through the ultrasonic nozzle, cool, and form liquid droplets of the desired size and density, the parameters being determined by the dimensions
15 of the expansion channel, its temperature and the prevailing pressure in it.

The method in accordance with the invention includes the following method steps: Filling of a target liquid into a container, in which a high pressure is realized by means of a non-reactive gas, brief opening of the
20 receptacle by a pulsed electromagnetic valve, pulsed introduction of the target liquid into an expansion channel, heating of the expansion channel such that a supersaturated liquid vapor is generated, cooling of the vapor during passage to a supersonic valve connected to the expansion channel, discharge of the droplets from the output opening of the nozzle into a
25 vacuum.

In some embodiments of the invention a pulsed electromagnet valve is used operating in the ms range and, more particularly, at a pulse duration of 2 ms. At each switching of the vale the target liquid is pressed into the
30 expansion channel and the corresponding vapor is pressed into the supersonic nozzle. An expansion channel of several mm to several cm in length and a diameter of several 100 µm to the mm range and a supersonic

nozzle of with a conical opening angle 2Θ of several degrees to several 10°, an input opening of several 100 μm diameter and a conically shaped section several mm in length are used. During its passage to the discharge opening of the nozzle the supersaturated gas is cooled in the nozzle. This leads to the

5   formation of liquid droplets. It is further to be mentioned that in addition to the mentioned parameters of the expansion channel the diameter of the nozzle also determines the diameter of the liquid droplets emerging from the nozzle opening into the vacuum.

10   Compared to the prior art which constitutes the basis of the invention, the valve in accordance with the invention regulates the direct feeding into an additionally provided expansion channel in which the target liquid is heated. The thus present supersaturated gas is fed to the discharge opening of the nozzle and cooled which leads to the formation of droplets in the nozzle. By

15   contrast, in the known arrangement, the valve switches the nozzle directly into its closed and open states which substantially lessens the effect on the formation and extent of the droplets and their collimation.

        The invention will hereafter be described in greater detail with

20   reference to drawings, in which:

        Fig. 1 schematically depict the structure of an apparatus in accordance with the invention;

        Fig. 2 is a curve of the switching pulse of the valve and the associated

25   intensity of the liquid spray generated as a function of time;

        Fig. 3 is a curve of the width of expansion of the liquid spray in air and in vacuum as a function of the distance from the discharge opening of the nozzle;

        Fig. 4 is a curve of the density of the liquid spray as a function of the distance

30   from the discharge opening of the nozzle; and

        Fig. 5 is a curve of the relative intensity of scattered light measured by CCD.

The apparatus in accordance with the invention for generating a droplet target is provided with a pulsed electromagnetic valve 1. The valve closes a receptacle (not shown), in which target liquid is maintained at a pressure of 35 bar by gaseous nitrogen. The target liquid may be water, but

5   in principle it may be any other liquid as well. The valve 1 opens and closes at a pulse duration of 2 ms and, in its open phase, discharges water droplets into an expansion channel 2 of 1 mm diameter and 15 mm length. By means of a heater 3 a temperature of 150 °C is generated in the expansion channel 2. The expansion channel 2 is separated from the valve 1 by an insulator 5.

10 The supersaturated water vapor now present at the end of the expansion channel 2 is now fed through a supersonic nozzle 4. The nozzle 4 has an opening angle of $2\Theta = 7°$, an input opening of 500 μm diameter and a conical section of 8 mm length and generates sub-μ liquid droplets into the vacuum. A droplet target which can be continuously generated and which makes

15 possible a chronologically unlimited operation is formed at the discharge opening of the supersonic nozzle 4.

Fig. 2 displays a curve of the switching pulse of the valve and the associated intensity of the generated liquid spray as a function of time at a

20 distance of 1 mm from the discharge opening of the nozzle. In this measurement during which the radiation generated by a cw He-Ne-laser was directed to and scattered by the droplet target, and the intensity of the scattered radiation at a spacing of 1 mm from the nozzle opening was determined, the pulse duration of the valve was 2 ms. It can be seen that the

25 major portion of the spray pulse occurs about 1 ms after opening of the valve.

Fig. 3 shows a curve depicting the spread of the liquid spray as a function of distance from the discharge opening of the nozzle in air and in vacuum. Compared to results known from the prior art, it can be seen that

30 the collimation resulting in accordance with the invention is improved by about 30%.

The spread geometry of the generated cloud of droplet spray may be defined as R = (.32 ± .32) x h + r, R being the radius of the spray/fog cloud, h being the distance from the supersonic nozzle and r being the radius of the discharge opening of the supersonic nozzle. A zero distance corresponds to

5   the discharge opening of the supersonic nozzle.

Fig. 4 discloses a curve which depicts the dependency of the density of the droplets within the spray as well as the dependency of the mean atomic density in the spray upon the distance from the discharge opening of the

10   nozzle. The measured droplet density varies as regards droplets of a .15 µm diameter from $(1.6 \pm .5) \cdot 10^{11}$ droplets per cubic centimeter (or a mean molecular density of $8 \cdot 10^{16}$ cm^{-3}) at a distance of 20 mm from the discharge opening. At this droplet size this constitutes a droplet density higher by up to three orders of magnitude than in currently described spray droplet source.

15   This is important for the conversion of irradiated laser energy.

Fig. 5 depicts the measurement data of the scattered light intensity as a function of the viewing angle. The solid line represents the theoretical distribution of the scattered light intensity of particles of a diameter of .15 µm.

20   The correspondence with the measurement data indicates a closer distribution of the droplet sizes than in the prior art so that - unlike in the prior art - there is no need for a droplet size filter and that in this manner the effective droplet density is advantageously increased.

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